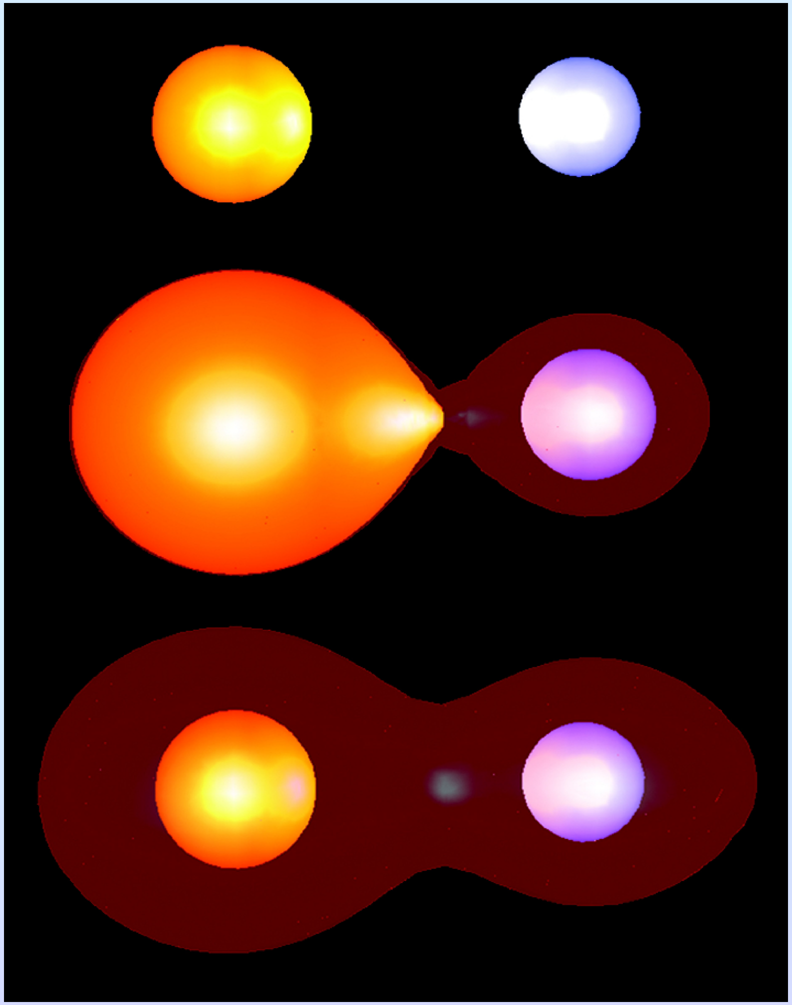
Unstable Mass Transfer

When the mass ratios are large, or when the donor star has a deep convective layer (so $R \propto M^{-1/3}$), mass loss will occur on a dynamical timescale. The result will be common envelope evolution, in which

- The energy released from the orbit will be greater than the binding energy of the envelope. The envelope will be ejected in all directions (but preferentially in the plane of the orbit).

- The system's semi-major axis will shrink (by a factor of ~ 100) and the orbit will circularize on a dynamical timescale.

Eventually, the star reaches the denser layers of the giant, and mass ejection becomes harder. The mass ejected is similar to the mass of the companion.



Common Envelope Evolution

Towards the end of the common envelope phase, there (probably) will still be two stars: a low mass star still burning hydrogen, and a helium proto-white dwarf. The separation will be very small, and the hot core will ionize the ejected envelope, producing a planetary nebula.

Common Envelope Evolution

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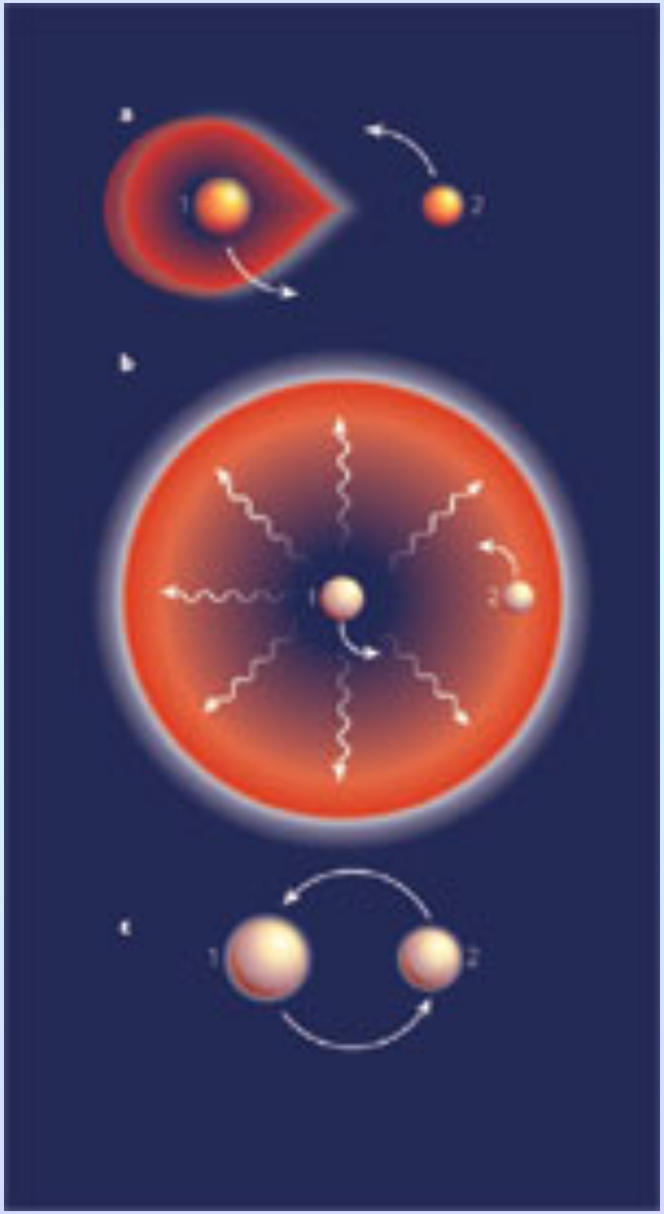
Common Envelope Evolution

At the end of common envelope evolution:

- The binary will have a very small separation, less than the radius of the Sun.
- Since the separation is so small, the remains of the main sequence companion may/will overflow its Roche Lobe. It will then transfer mass onto the white dwarf on a thermal or nuclear timescale. This matter will form an accretion disk.

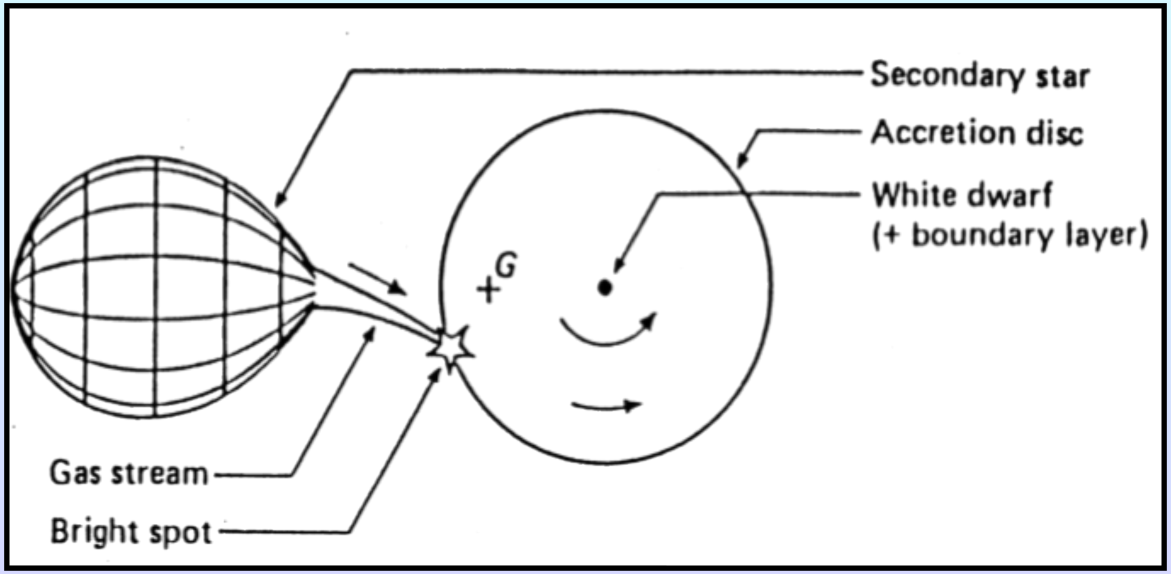


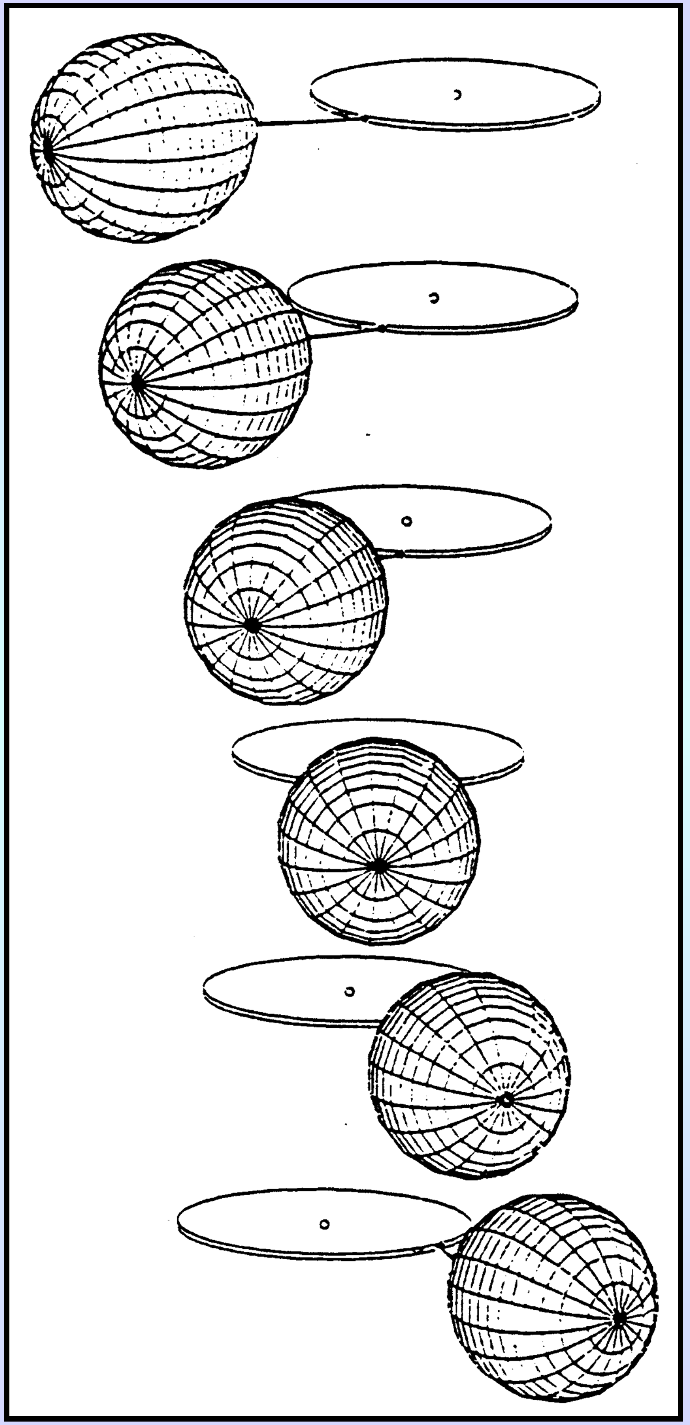
Accretion Disk Formation

• Particles that are lost via the L1 Lagrange point have trajectories that miss the compact object.

• The mass-loss stream self-intersects after coming about the compact object and eventually forms disk.

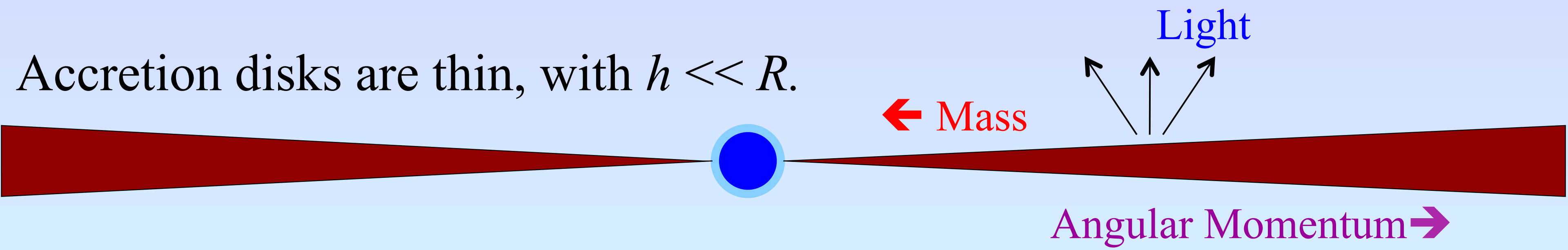
• Continued accretion from L1 hits the outer rim of this disk.



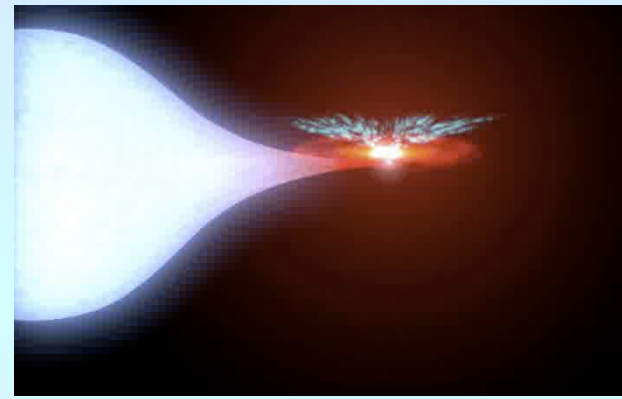


Accretion Disk Basics

Accretion disks are thin, with $h << R$.



The interaction of particles in the disk will cause material to spiral in towards the central object, and release energy. Since the orbital velocity of any particle is



$$\frac{mv^2}{r} = \frac{GMm}{r^2} \quad \Rightarrow \quad v^2 = \frac{GM}{r}$$

an object spiraling from radius r to the companion's surface must release

$$\Delta E = \frac{GM}{R_*} - \frac{GM}{r} + \frac{1}{2}v^2 = GM\left(\frac{1}{R_*} - \frac{1}{2r}\right)$$

Note: $E = mc^2 \Rightarrow 1\mathrm{M}_\odot = 2 \times 10^{54}$ ergs!!

Energy to be Radiated

Object	ergs/$\mathrm{M}_\odot$
Main Sequence Star	$\sim 3 \times 10^{48}$
White Dwarf	$\sim 4 \times 10^{50}$
Neutron Star	$\sim 2 \times 10^{53}$
Black Hole	$\sim 9 \times 10^{53}$

Accretion Disk Basics

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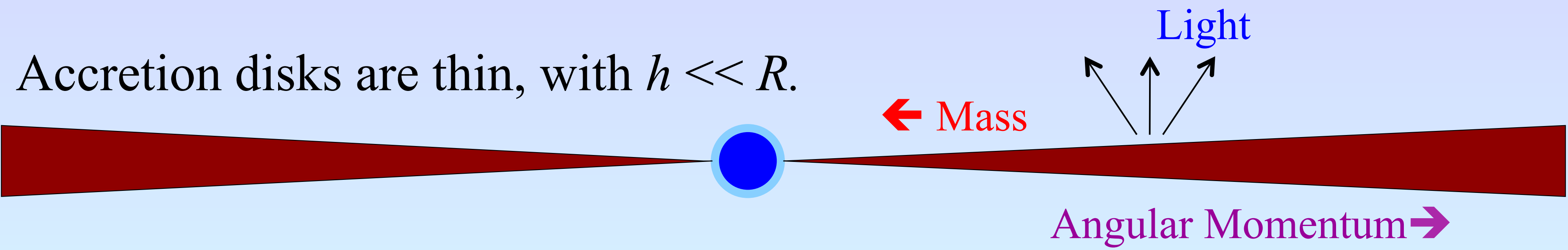
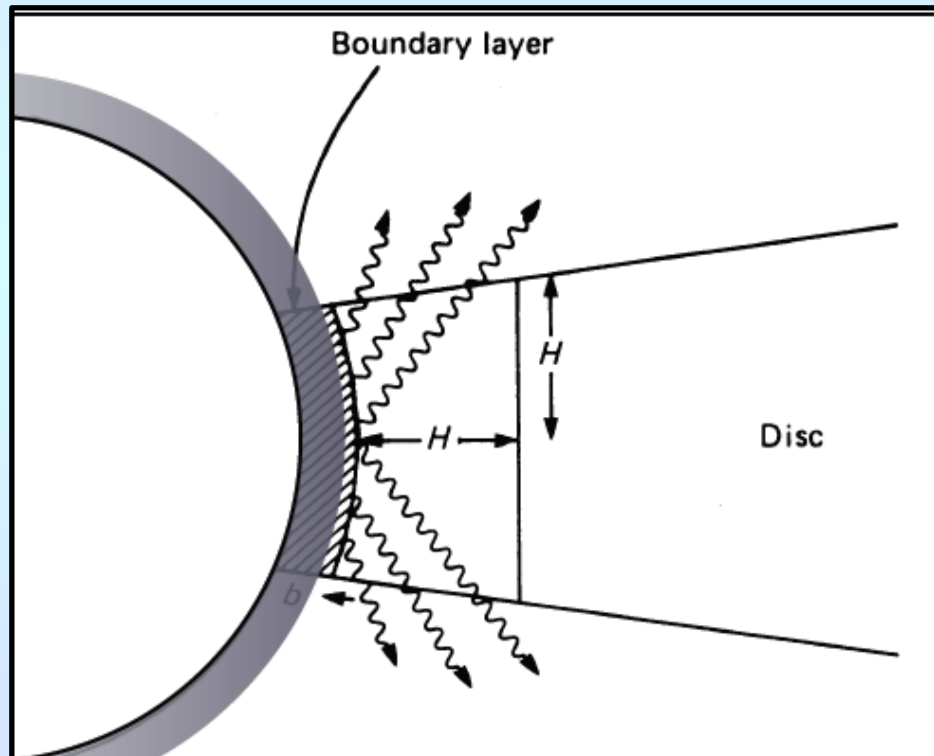


Note: the change in the potential energy of a particle dropped from infinity to the stellar surface is simply GM/r, but the kinetic energy just before impact is

$$\frac{mv^2}{r} = \frac{GMm}{r^2} \quad \Rightarrow \quad \frac{1}{2}v^2 = \frac{1}{2}\frac{GM}{r}$$

Thus, half the energy must be lost during accretion, and other half during the impact at the boundary layer.



Accretion Disk Basics

Energy is released from an accretion disk via friction, or *viscosity,* **ν**. The origin of the viscosity is poorly known, but is likely either turbulence (eddies) or magnetic field tension. In either case, $\boldsymbol{\nu} = \alpha\, c_s\, h$, where c_s is the local sound speed and h the disk thickness. All unknowns are lumped into α, which could be almost anything (and may vary with disk radius). The disk structure is then given by

$$\frac{h}{r} \approx \frac{c_s}{v_\theta} \qquad \nu\Sigma = \frac{\dot{m}}{3\pi}\left[1 - \left(\frac{R_*}{r}\right)^{1/2}\right] \qquad \frac{v_R}{v_\theta} \approx \alpha \left(\frac{c_s}{v_\theta}\right)^{-2} \quad \text{with} \quad \frac{c_s}{v_\theta} << 1$$

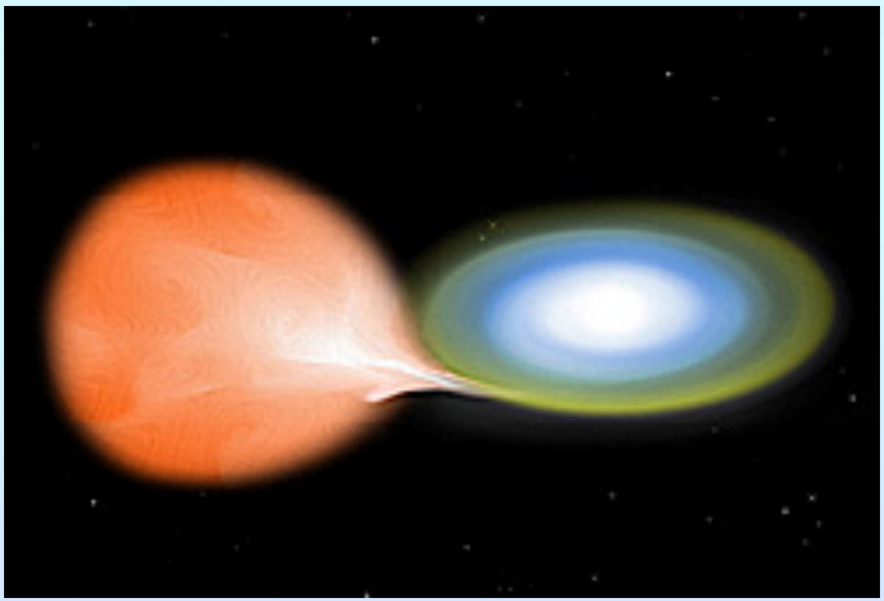
$$L(r) = \left(\frac{3GM\dot{m}}{8\pi}\right) r^{-3} \left\{1 - \left(\frac{r}{R_*}\right)^{-1/2}\right\} \qquad T(r) = \left(\frac{3GM\dot{m}}{8\pi R_*^3 \sigma}\right)^{1/4} \left(\frac{r}{R_*}\right)^{-3/4}$$

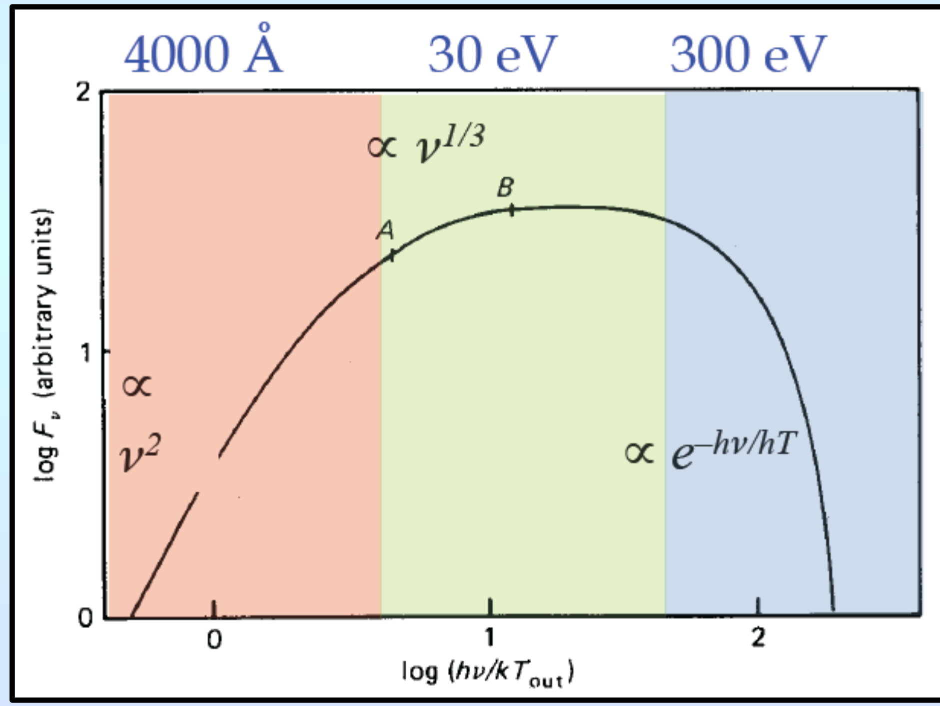
where v_R is the radial velocity of the accretion, v_θ is the rotation speed, and Σ the surface density of the disk. Note that the outside of the disk has a smaller rotation speed, hence a lower temperature and lower luminosity.

Accretion Disk Basics

Disk emission can be approximated by a series of concentric annuli, each with its own blackbody temperature and luminosity.

$$f_\nu = \frac{\cos i}{d^2} \int_{R_*}^{r_{\text{out}}} B_\nu\left[T(r)\right] \cdot 2\pi\, r\, dr$$



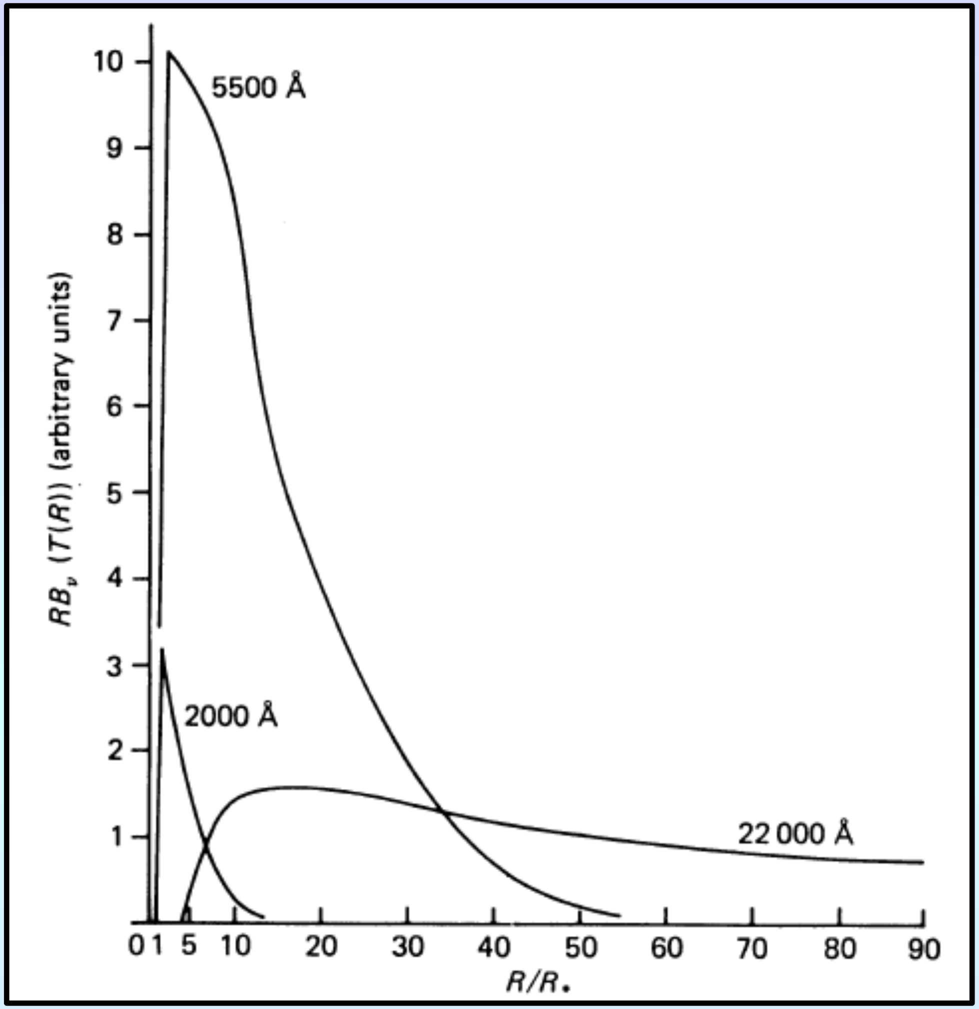


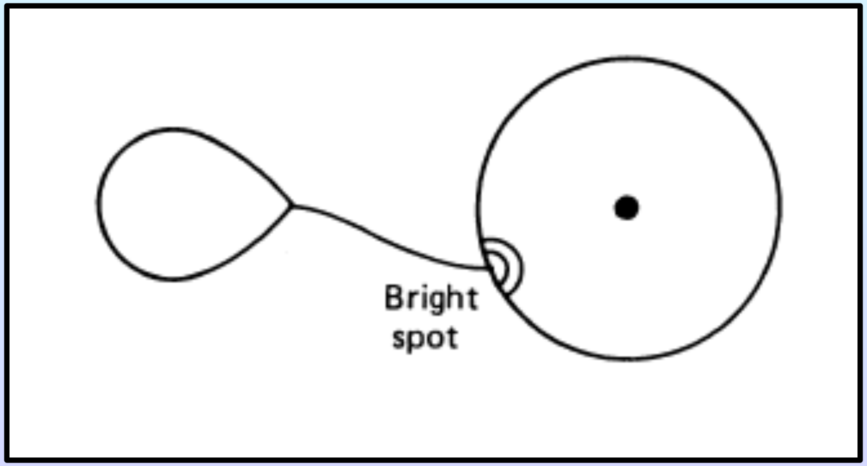
Typical accretion disks emit from the infrared through the X-ray and often outshine their stars.

Accretion Disk Basics

The area of the disk probed depends on the wavelength of the observation. Virtually the entire disk emits in the infrared, but the UV light comes exclusively from the disk's inner regions.

X-rays are emitted from the boundary layer, as the matter impacts on the surface.



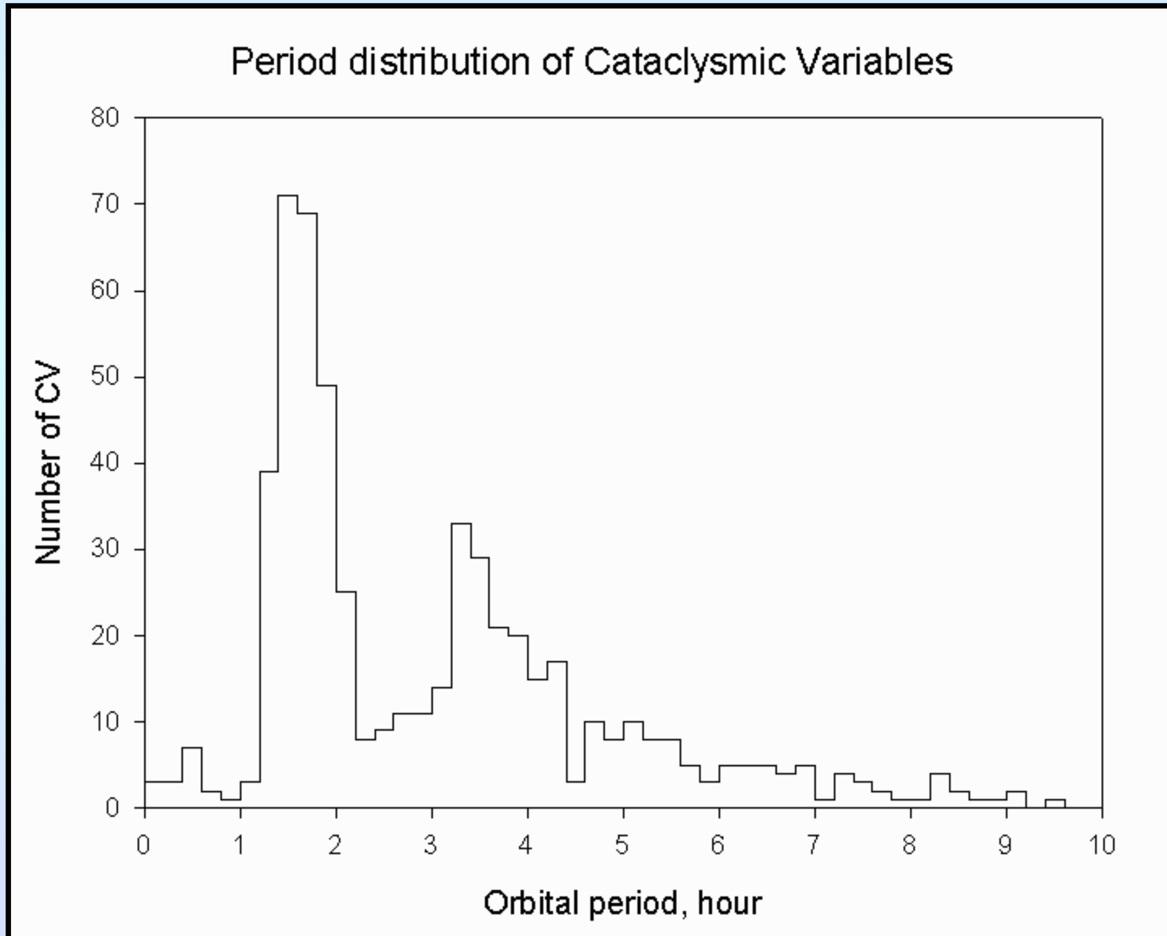


Note: accretion can spin-up a star, causing a white dwarf to rotate once a minute, and a neutron star to have a period of ~ 0.001 sec!

Cataclysmic Variables

If the accreting object is a white dwarf, the system is called a cataclysmic variable. There are different classes of CVs depending on the stability of the accreting process and the mode of accretion:

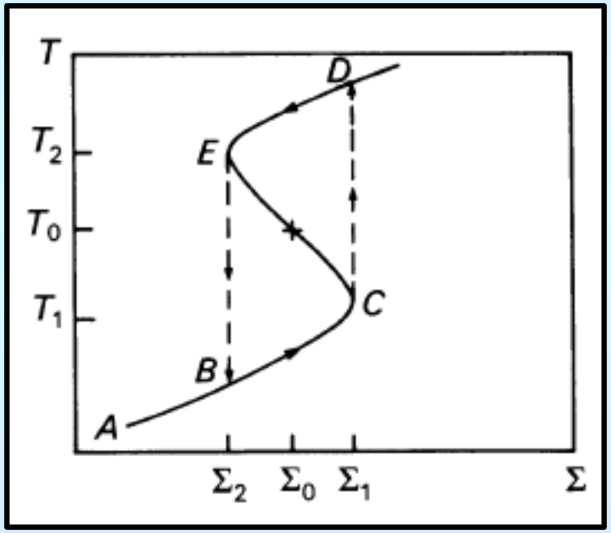
- Dwarf Novae
- Classical Novae
- Recurrent Novae
- Nova-like Variables
- AM Her Systems
- DQ Her Systems



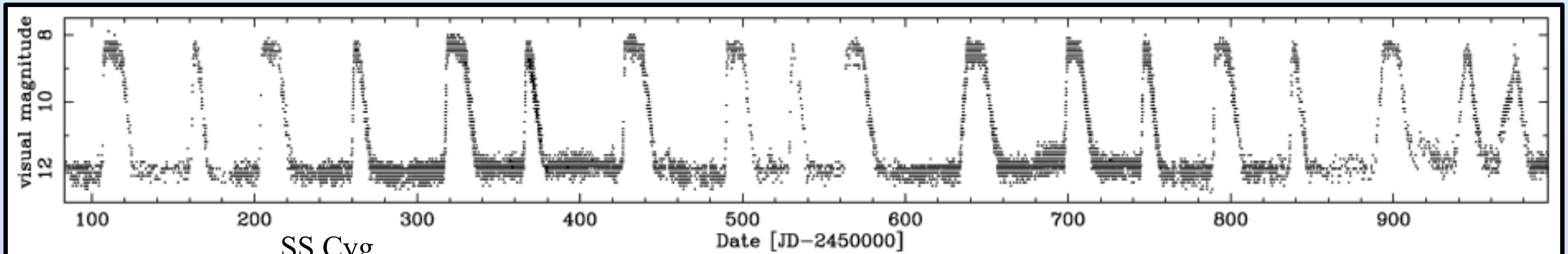
The absence of CVs with ~ 2 hour periods (the "period gap") is real and is probably due to accretion temporarily stopping.

Types of Cataclysmic Variables

• **Dwarf novae**: The accretion flow in disks is not necessarily stable. When the gas reaches a critical density/temperature, the opacity changes, the viscosity increases and the disk material is quickly dumped onto the white dwarf creating an outburst of several mag. The cycle repeats on timescales of weeks to years.



There are several sub-classes of dwarf novae, including **U Gem** (normal dwarf novae), **Z Cam** (which pause at intermediate brightness for months or years), and **SU Ursa Majoris** (which have normal and "super" outbursts).

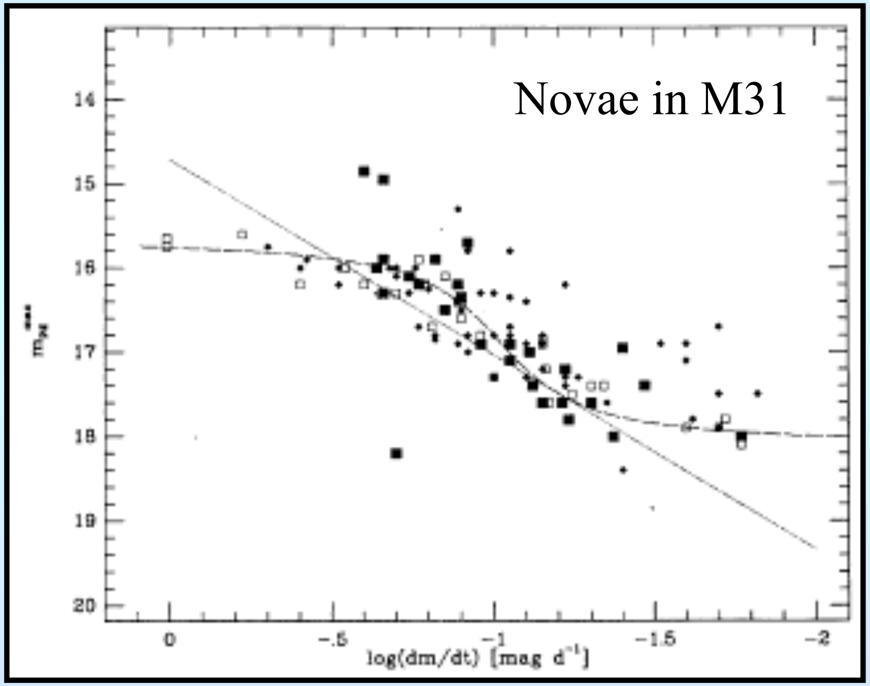


SS Cyg

Types of Cataclysmic Variables

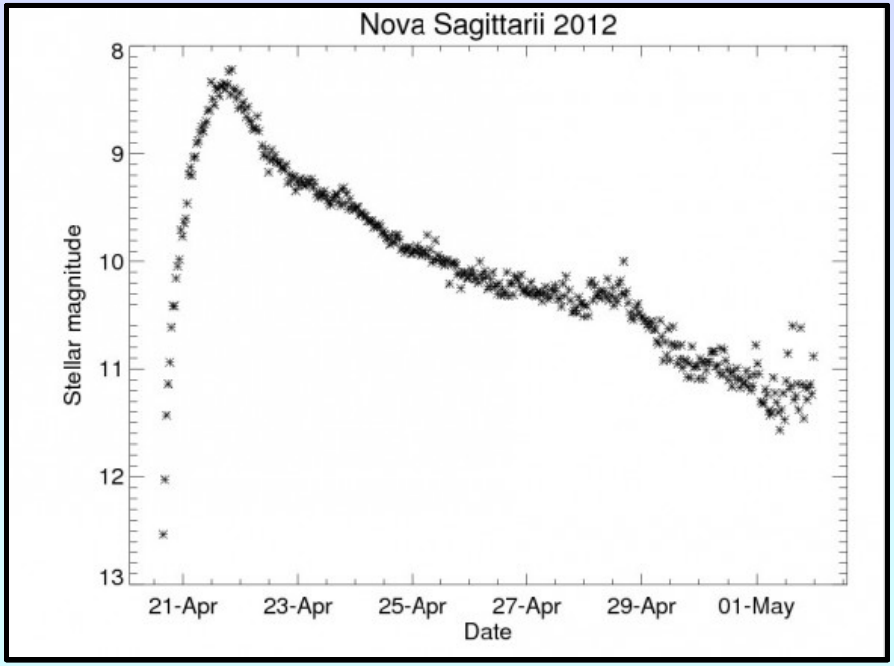
• **Classical Novae**: Accretion deposits hydrogen onto the surface of a white dwarf. In time, the hydrogen ignites in a thermal runaway (CNO burning) which lasts for weeks to a year. This outburst can be over 10 mag, with a brightness (usually) inversely proportional to decay time.

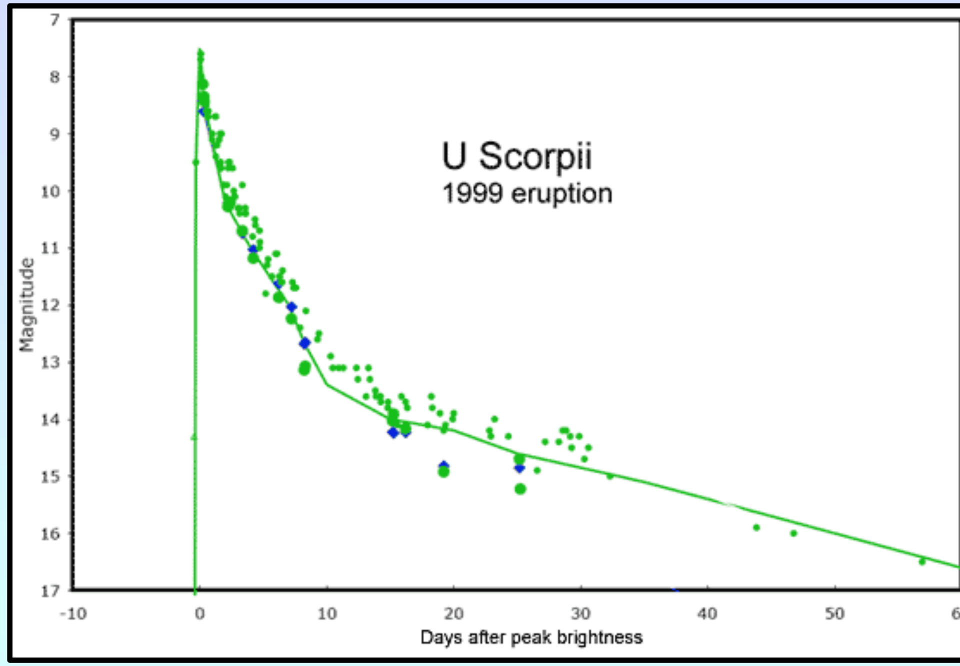
• **Recurrent Novae**: All classical novae (probably) recur. The time-scale for this depends on the white dwarf mass: it will take a 0.6 $M_\odot$ white dwarf many millennia to accumulate enough hydrogen to erupt, while a 1.2 $M_\odot$ object can erupt every few years.

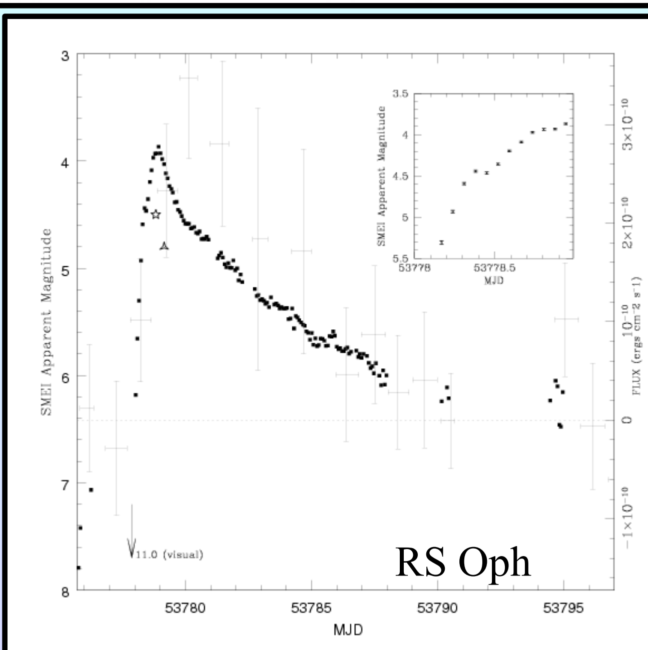


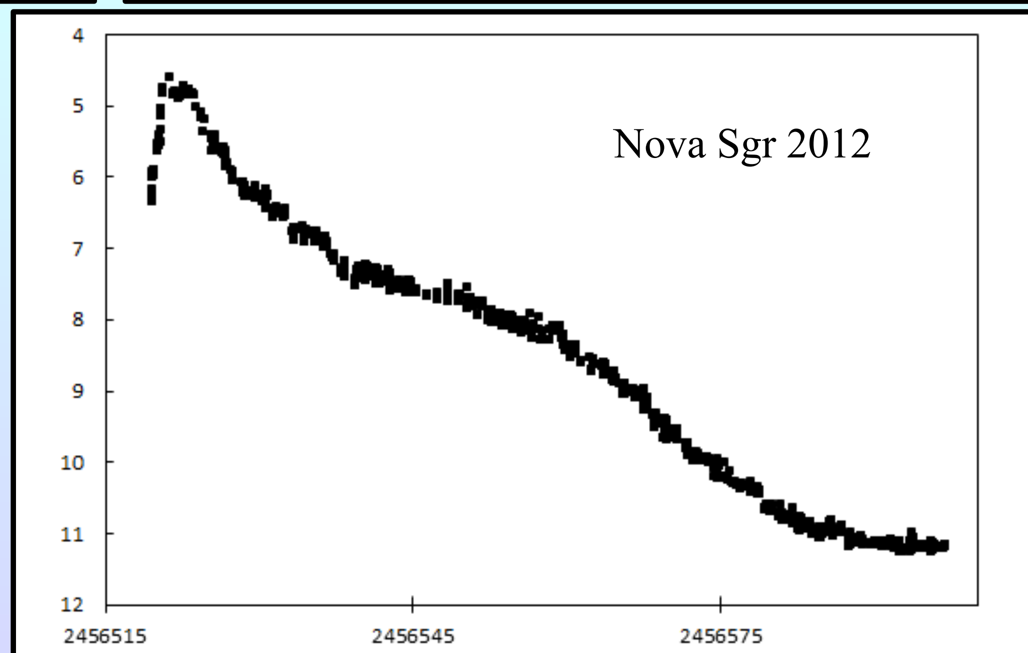
• **Nova-like Variables**: Non-eruptive cataclysmic variables. The mass transfer rates are higher than those of dwarf novae, thus avoiding the problem of disk instability. (The "standard star" Feige 24 is a nova-like star.)

Nova Light Curves



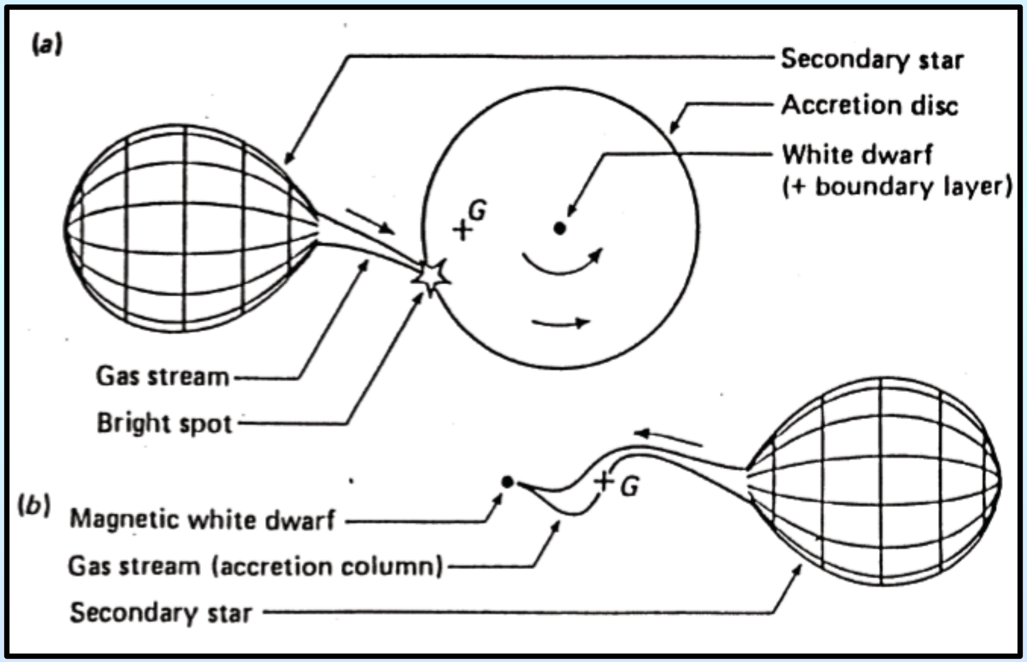


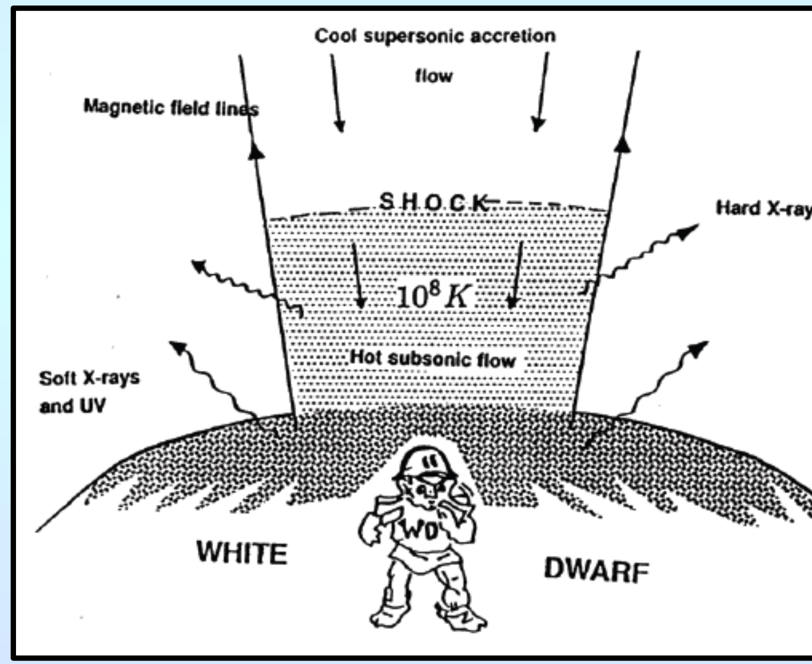




Types of Cataclysmic Variables

- **AM Her Stars** (Polars): Some white dwarfs are highly magnetized (~10^7 Gauss). Mass passing beyond the L1 point is forced to follow field lines until impacting on the magnetic poles of the white dwarf. No accretion disk is formed, and the system rotates as a solid body.

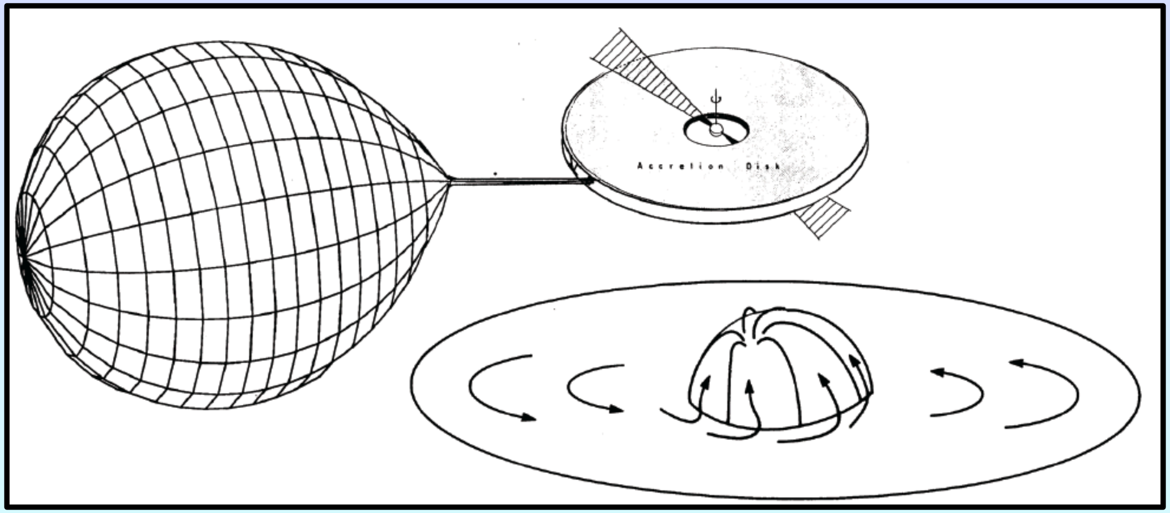


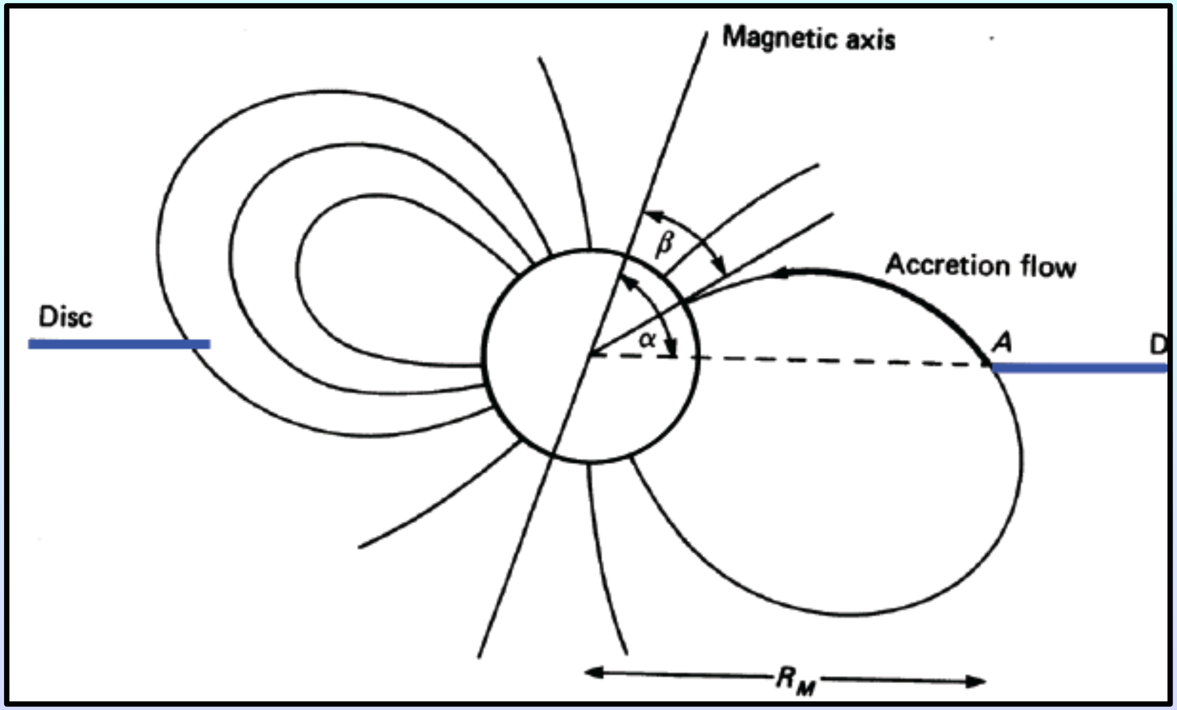


Because most of the emission is coming from the impact region and because the star is likely spinning rapidly (P ~ 1 min), these systems can show rapid variability, sometimes called “pulsations”.

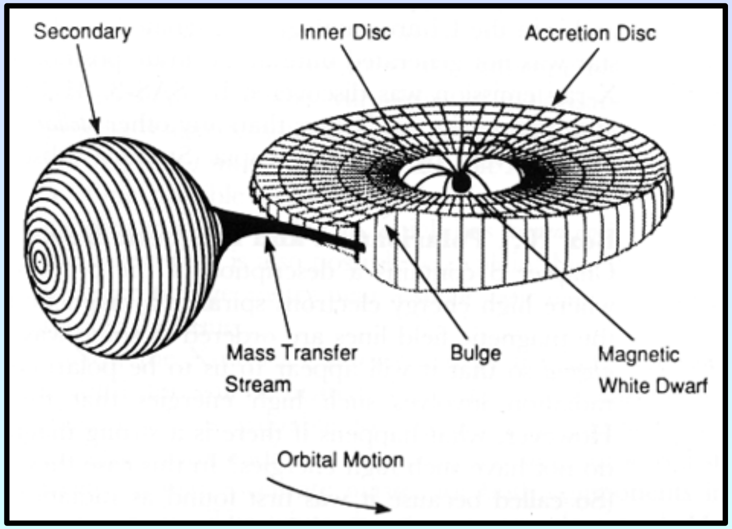
Types of Cataclysmic Variables

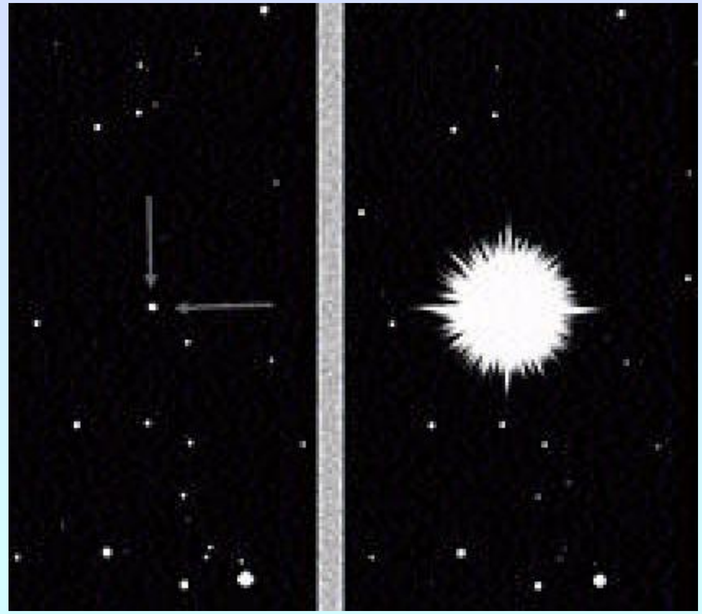
- **DQ Her Stars** (Intermediate Polars): The magnetic field strength is not quite as strong as in the AM Her stars, so an outer accretion disk exists. However, close to the white dwarf, the disk is disrupted as again, matter is forced to flow along with the field lines to the pole. Intermediate polars and AM Her stars may erupt as classical novae (such as DQ Her = Nova Her 1934).

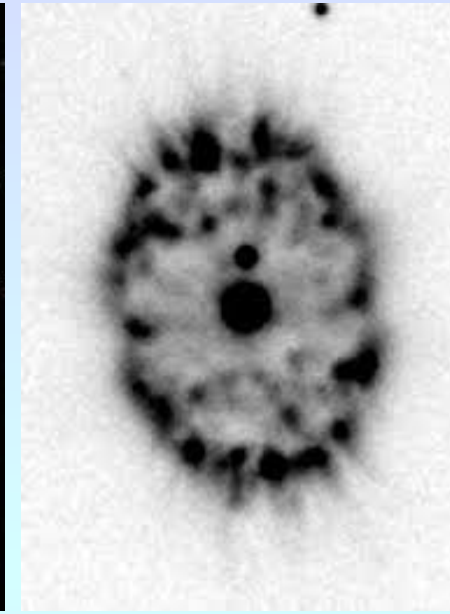


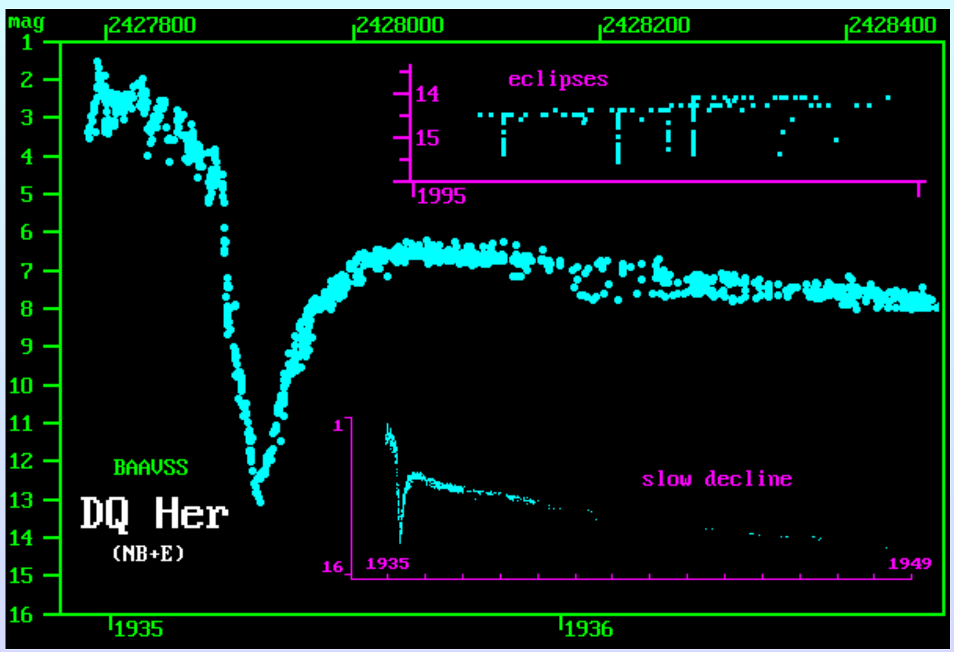


DQ Her (Nova Her 1934)









Other Accreting Binaries

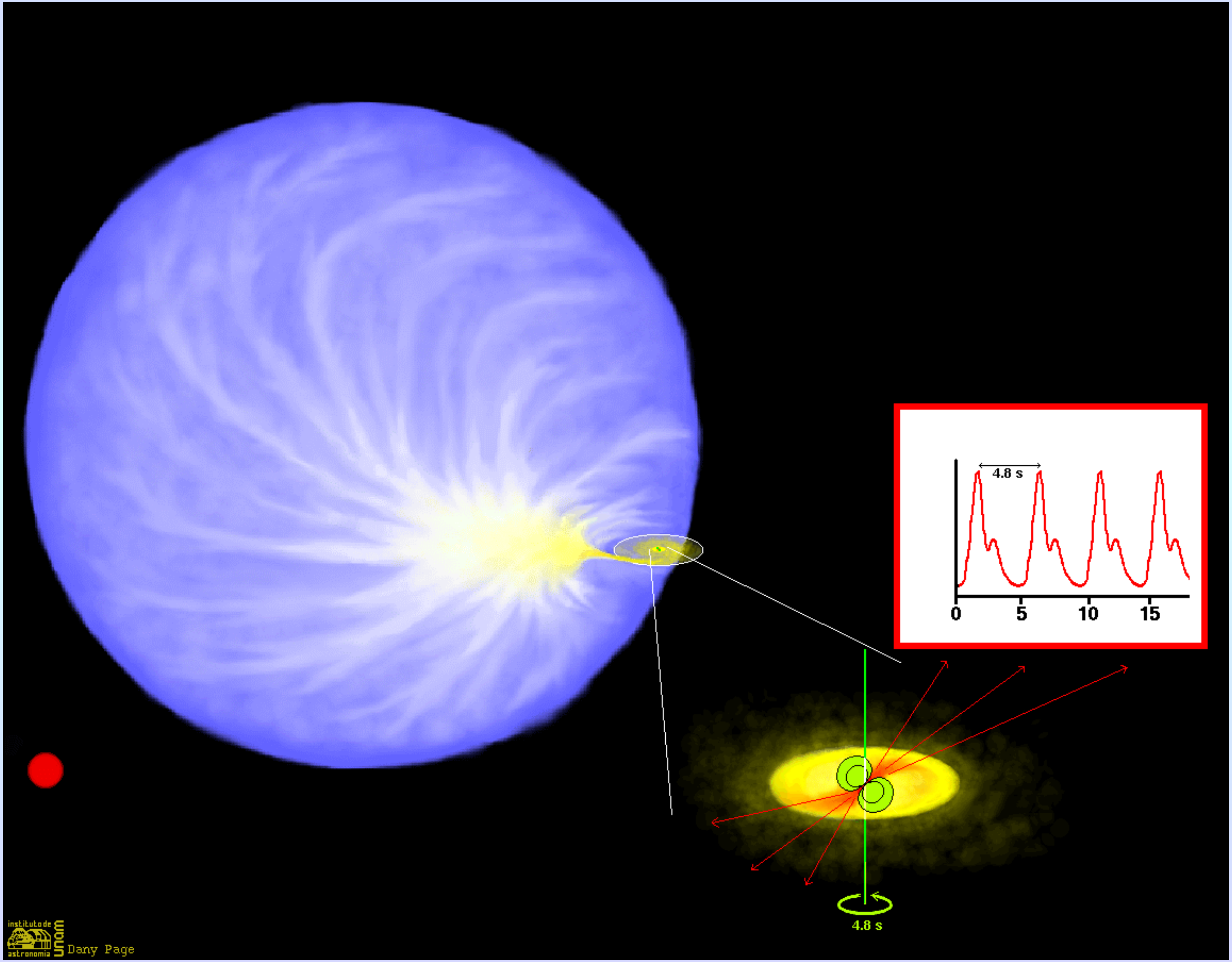
• **Super-Soft X-ray Sources**: Probably the result of continuous accretion and fusion of matter onto a white dwarf.

• **LMXBs** (Low-Mass X-ray Binaries): The donor object is a low-mass (convective envelope) star and the accreting object is a neutron star or black hole. Because of the greater potential, ~ 99% of their energy is released in the X-ray portion of the spectrum.

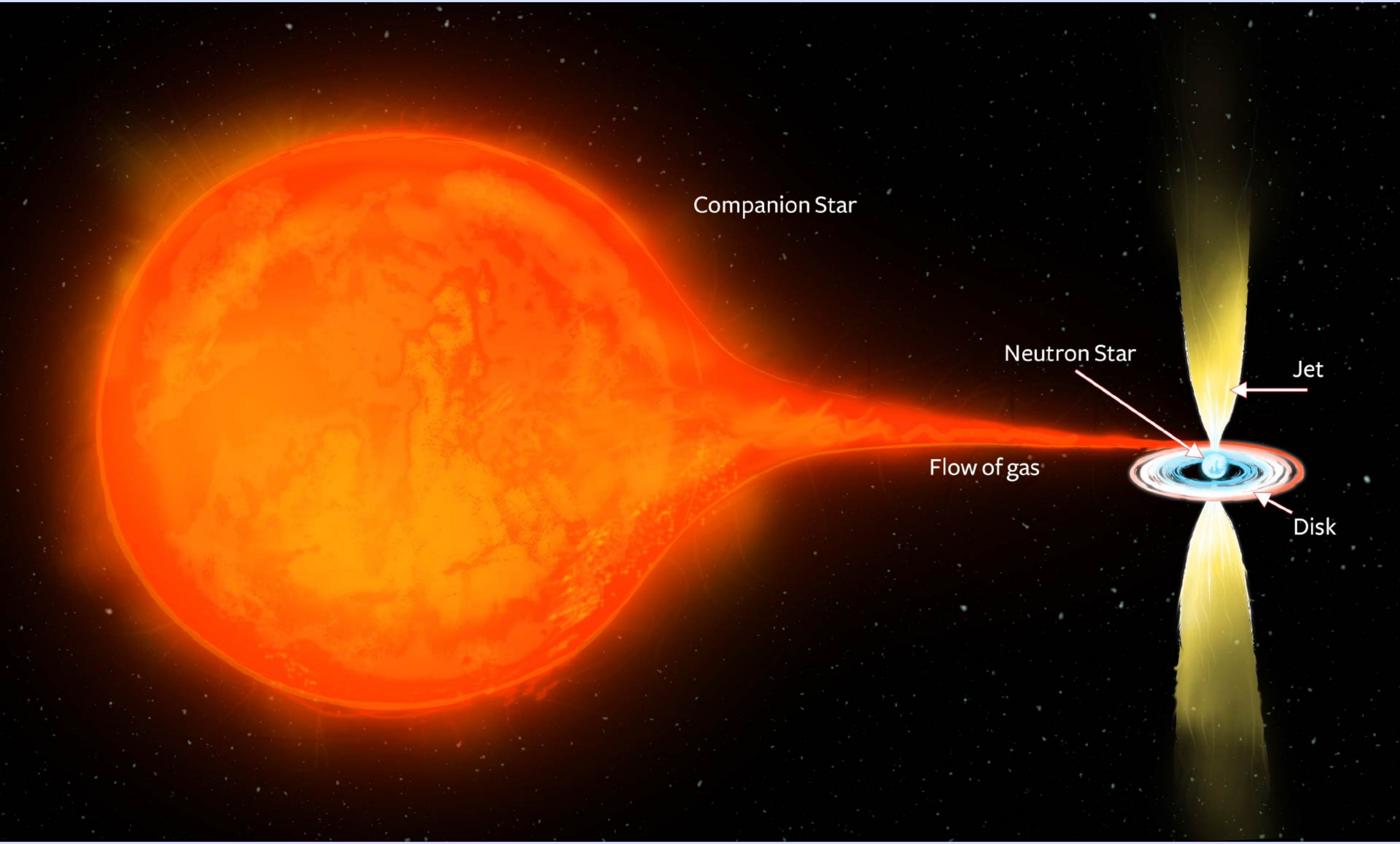
• **HMXBs** (High-Mass X-ray Binaries): The donor object is a high-mass star (spectral type O or B) with a strong stellar wind. The wind material is captured by the neutron star and produces X-rays when it impacts the surface.

• **Millisecond Pulsars**: Accretion can spin-up a dead neutron star (with $P > \sim 4$ sec) until it pulses again. It can spin it up even further, close to the break-up speed, so that the rotation period is milliseconds. Note: the hard X-rays coming from the accretion can evaporate the donor star, so some millisecond pulsars no longer have companions.

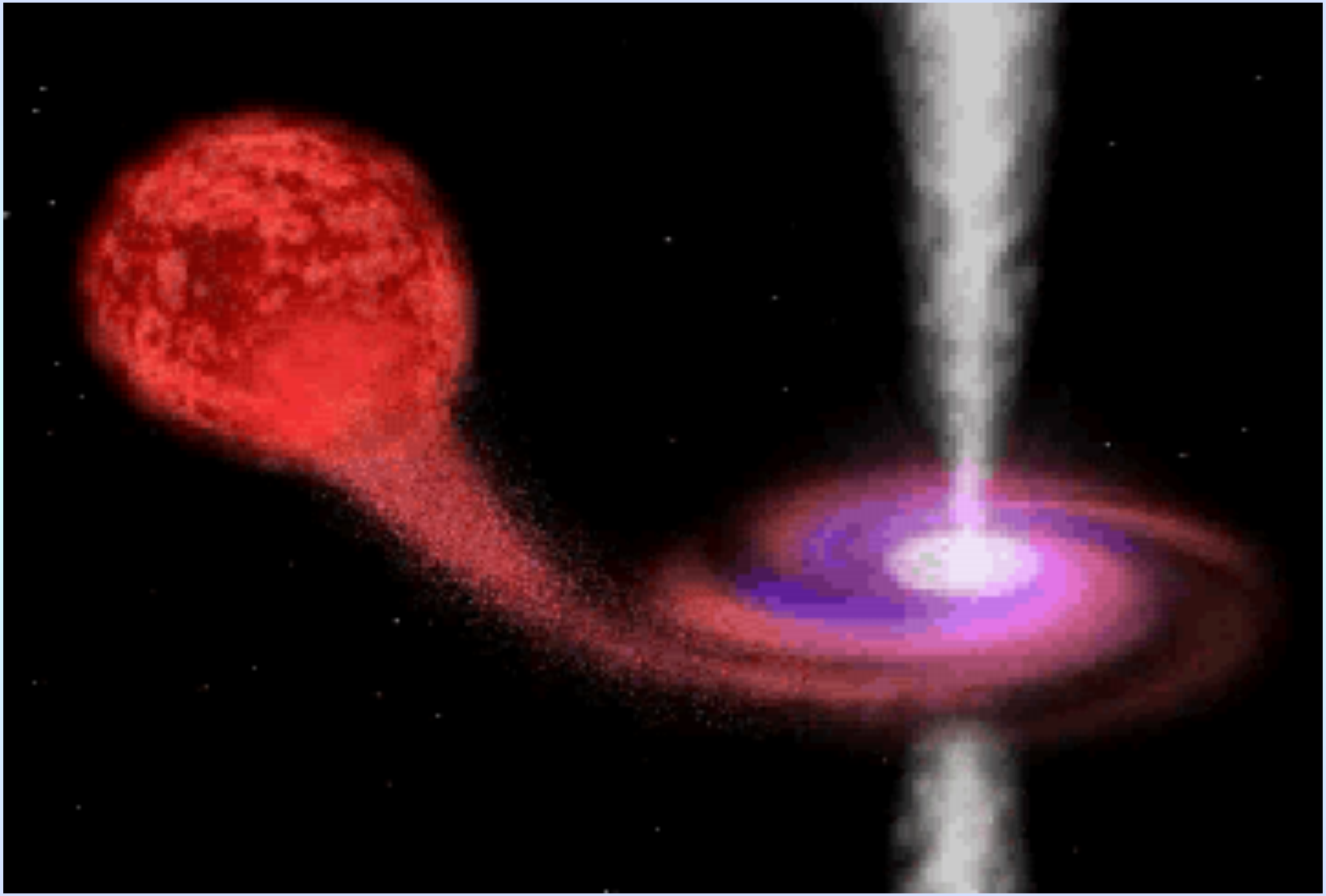
High Mass X-ray Binary



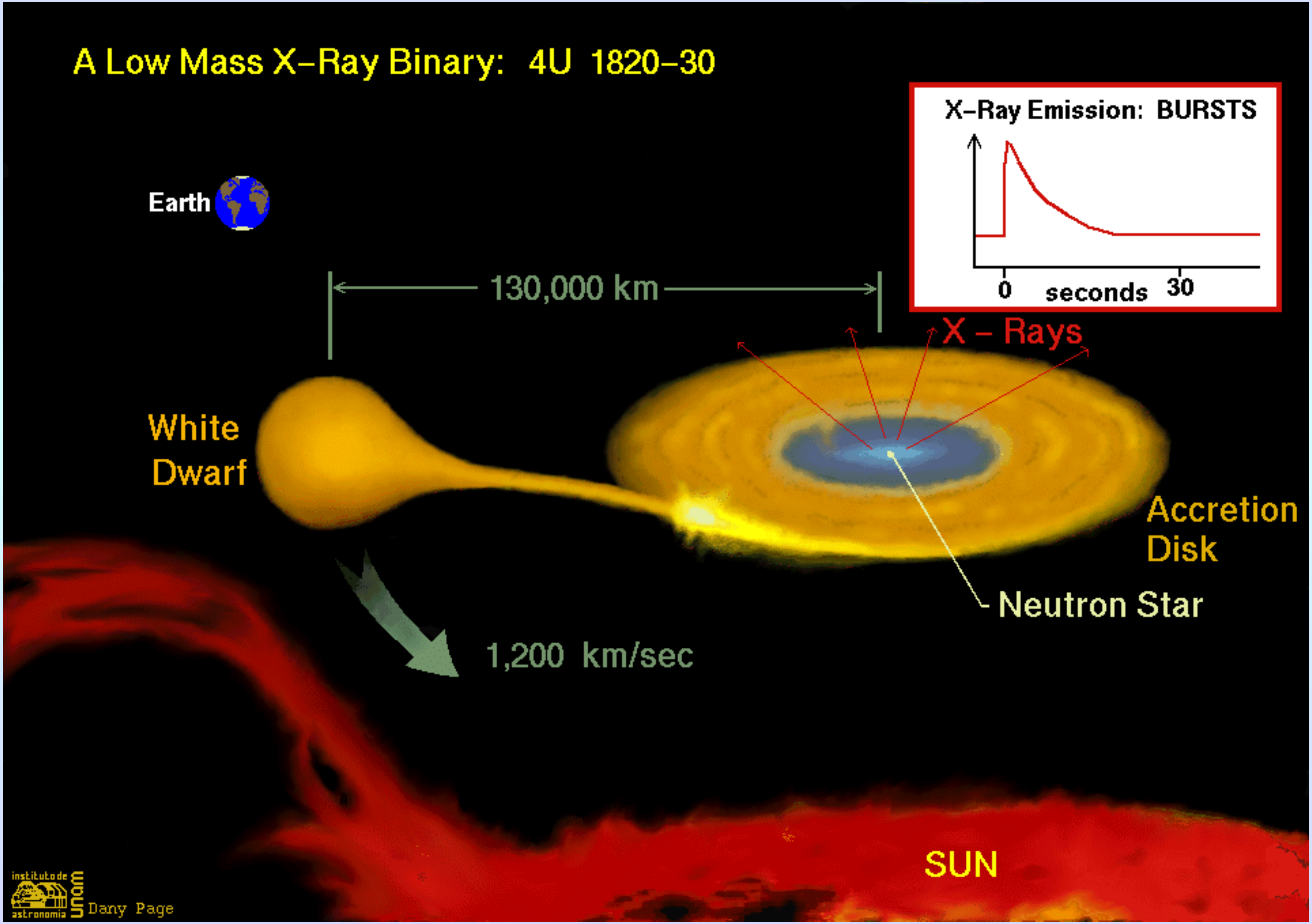
Low Mass X-ray Binary



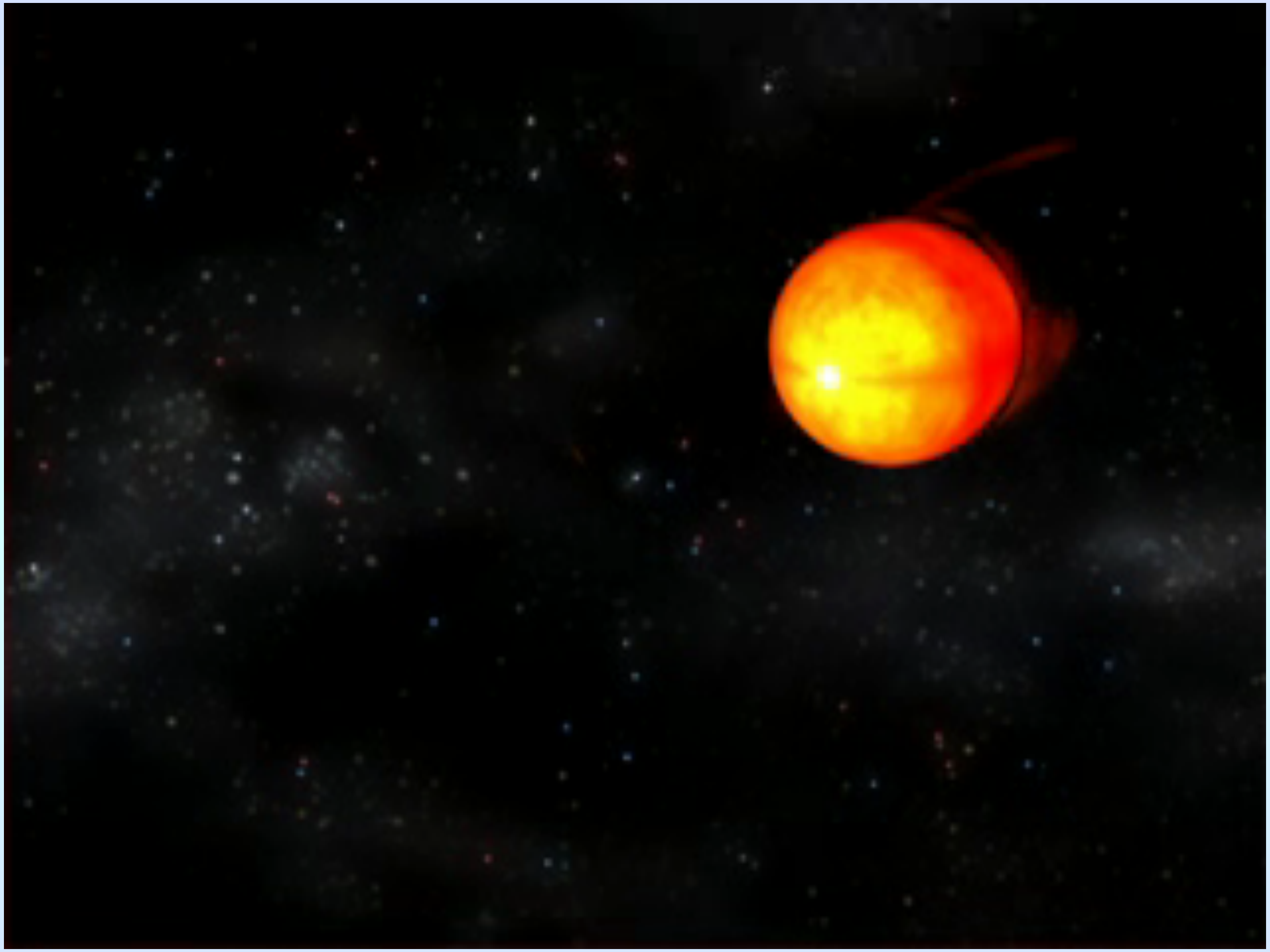
Low Mass X-ray Binary



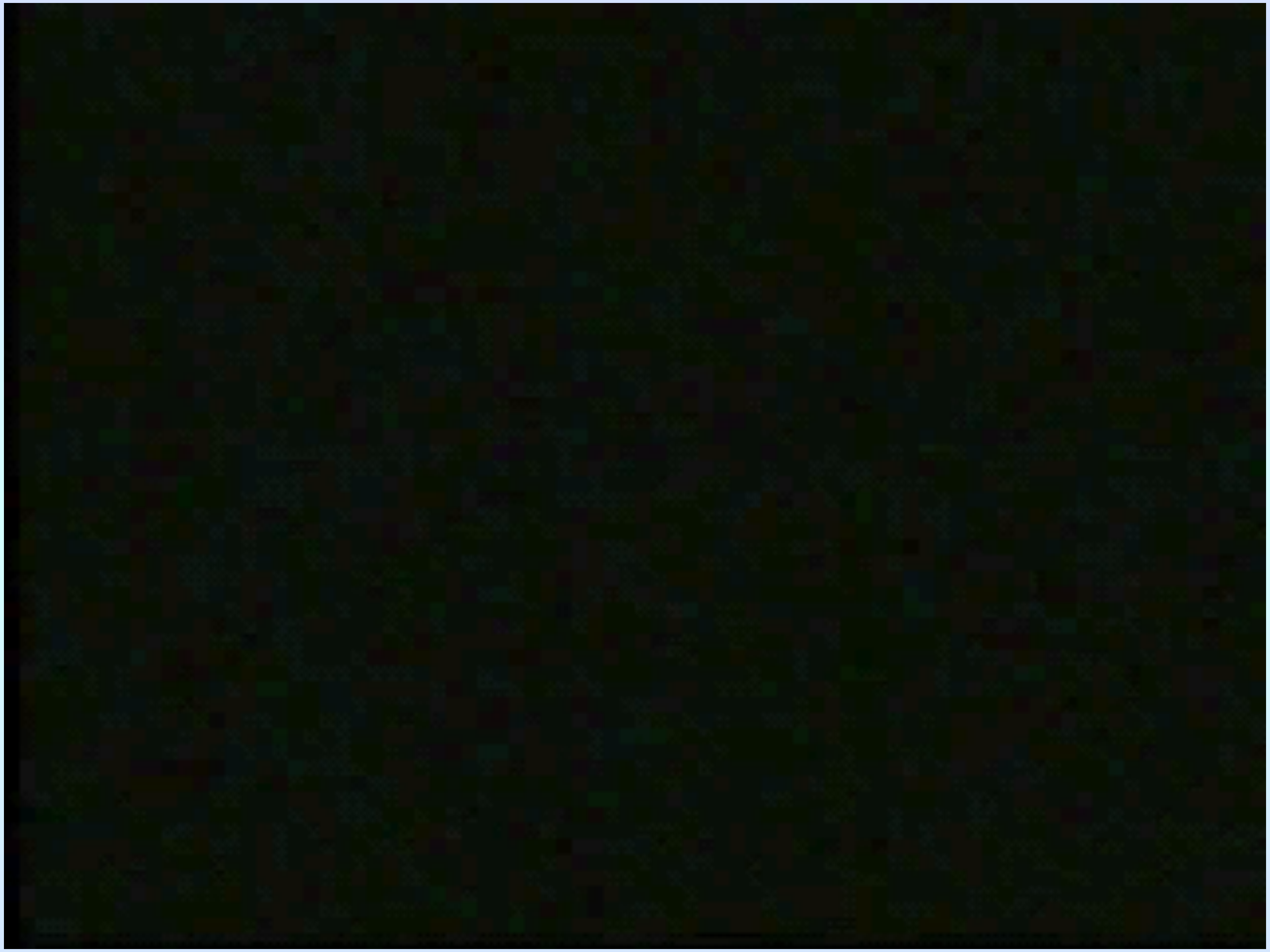
Low Mass X-ray Binary



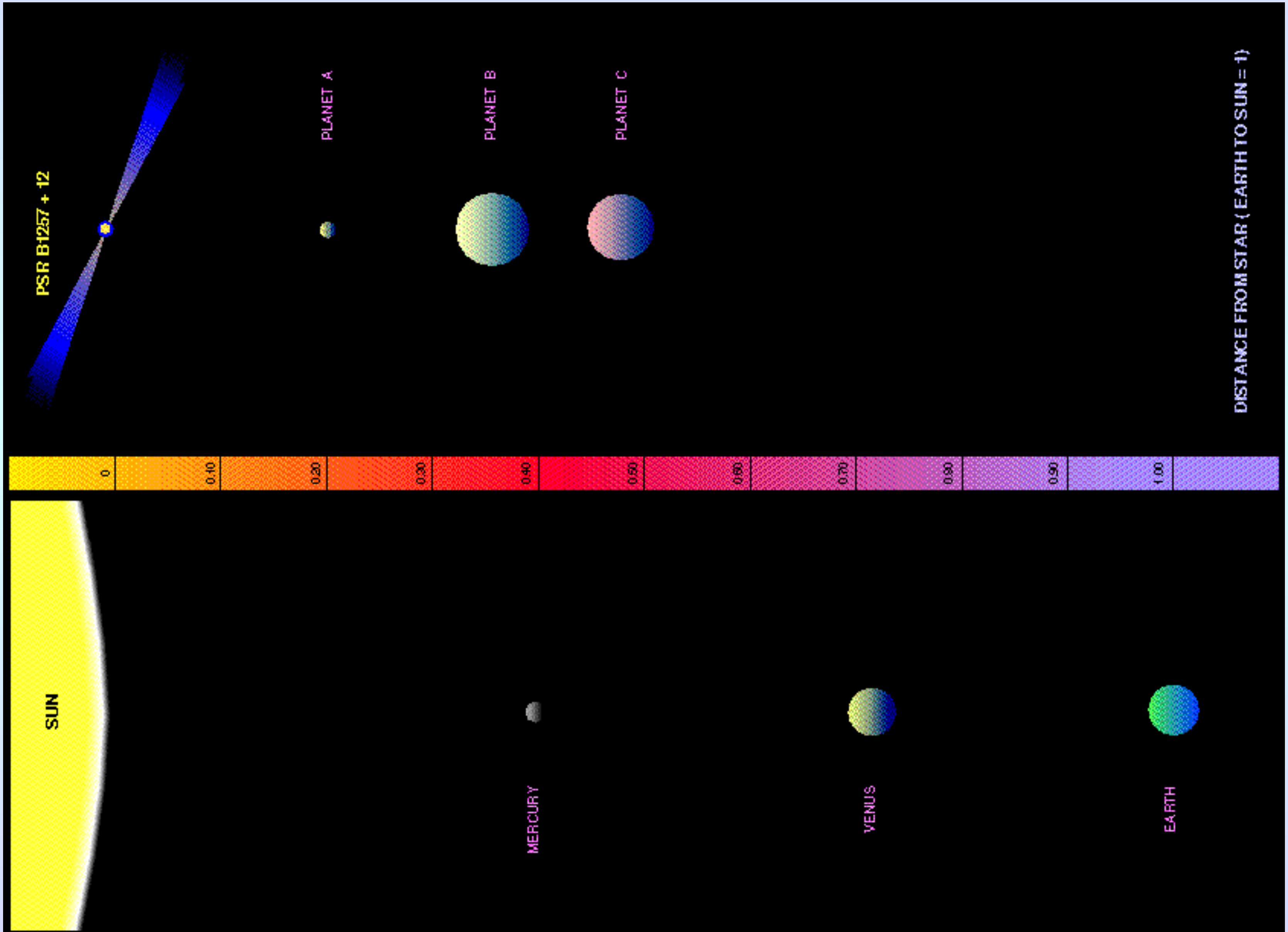
Millisecond Pulsar (with its companion)



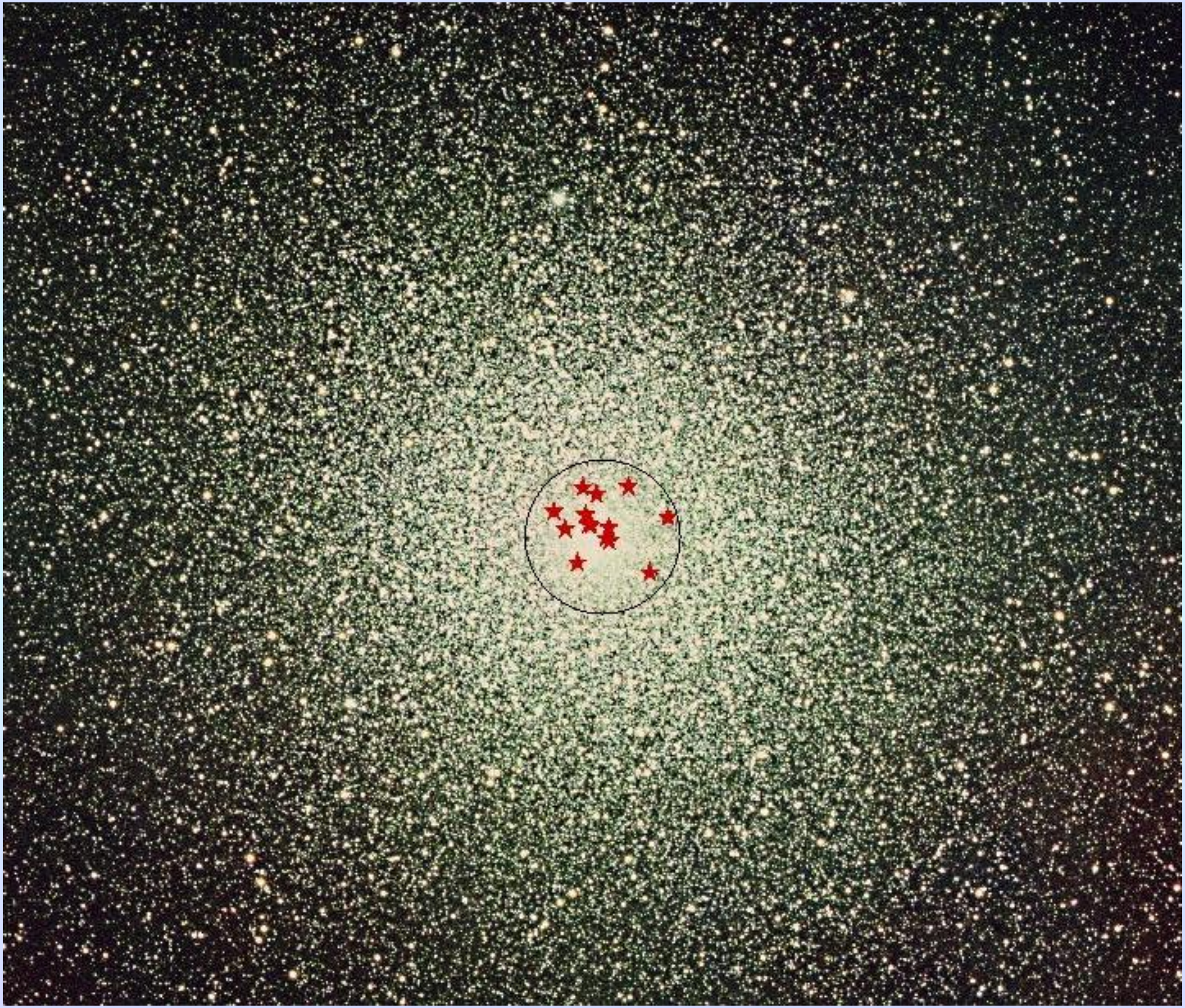
Millisecond Pulsar (no companion)



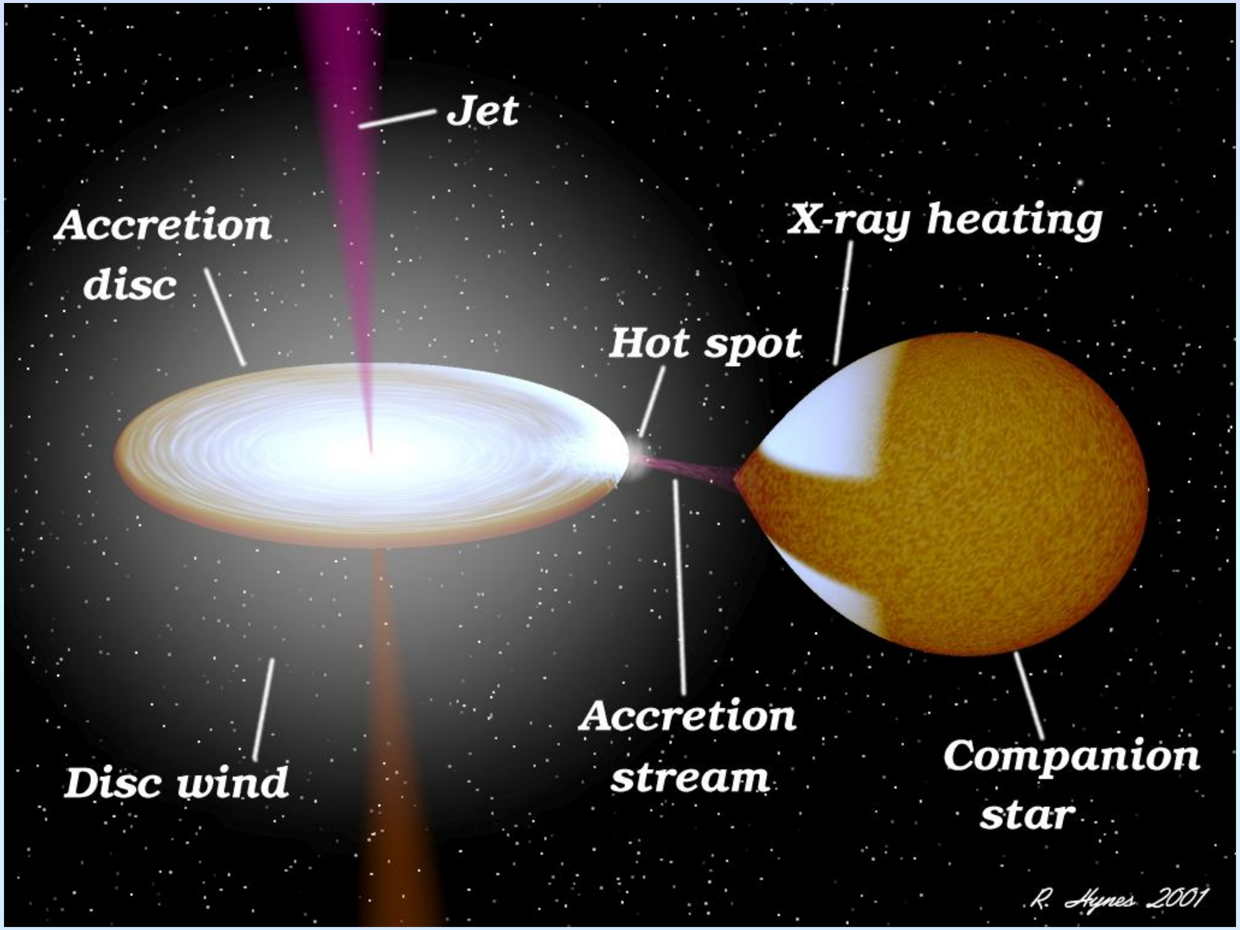
Millisecond Pulsar Planets Formed out of the Rubble



Millisecond Pulsars in Globular Clusters



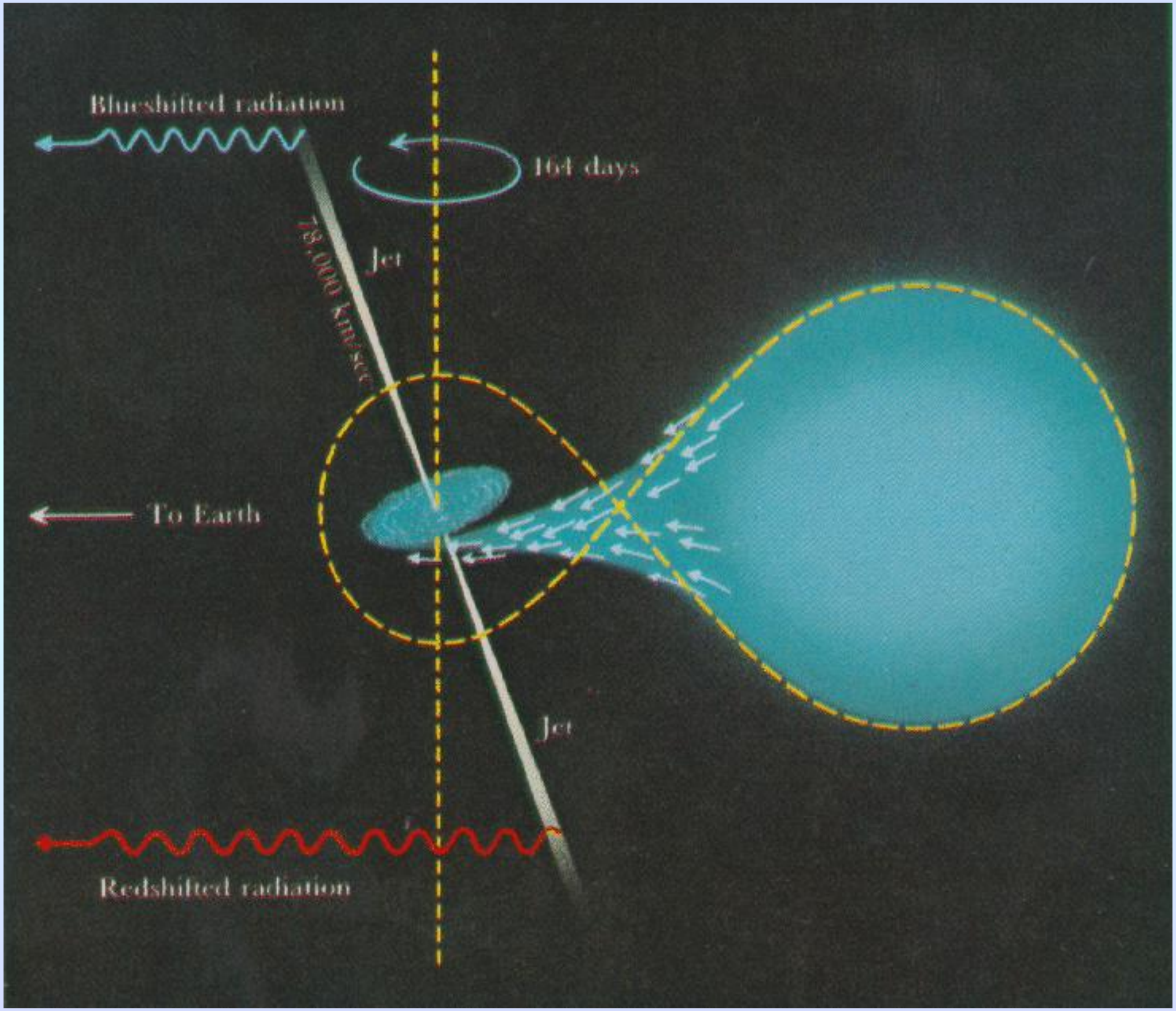
SS 433



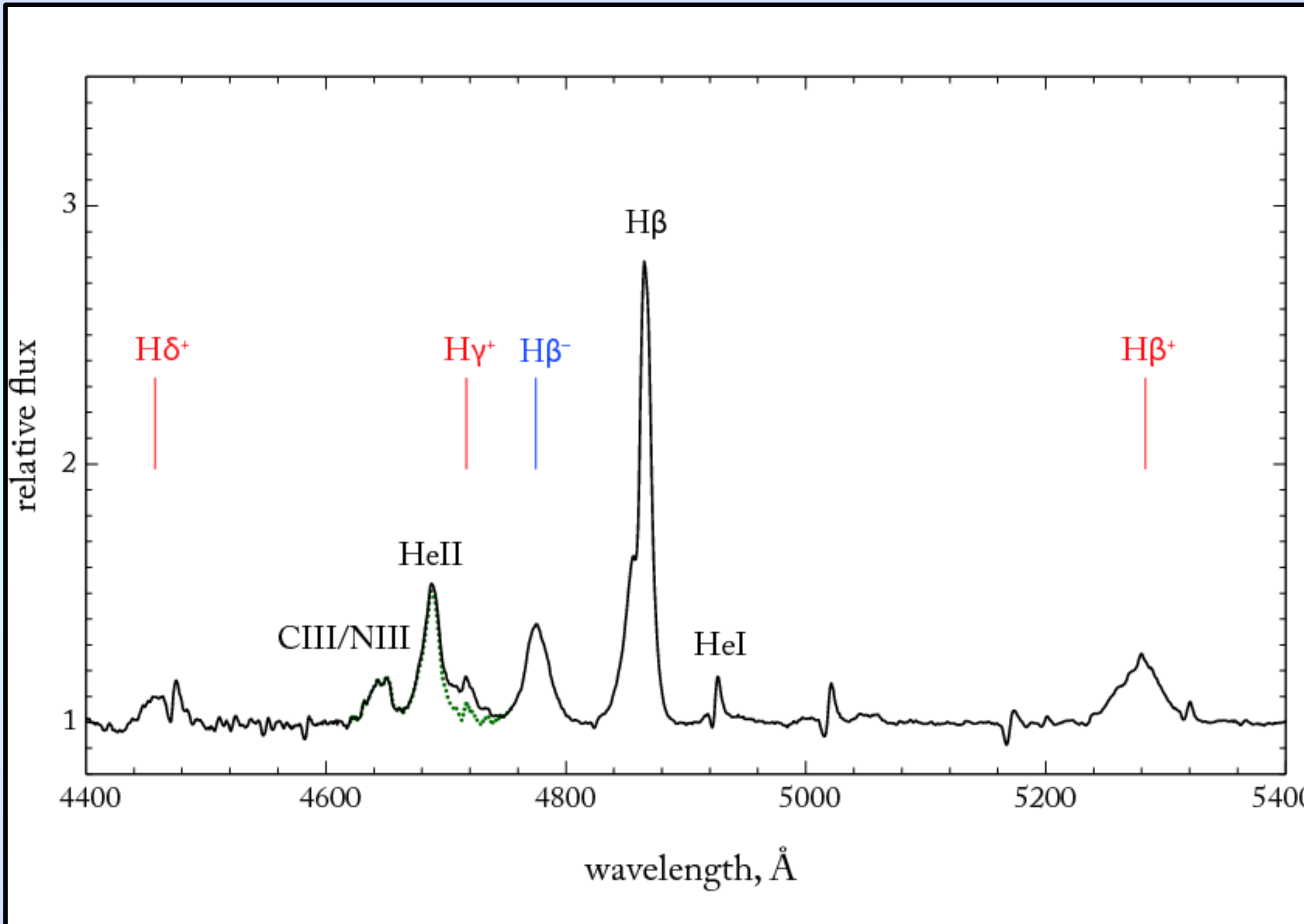
"They call it SS-433, and they found out it's-a coming towards Earth at 30,000 miles a second. *But* … it's also going away from Earth at 30,000 miles a second. It seems-a to be coming and-a going."

--- Don Novello, *SNL*, May 12, 1979

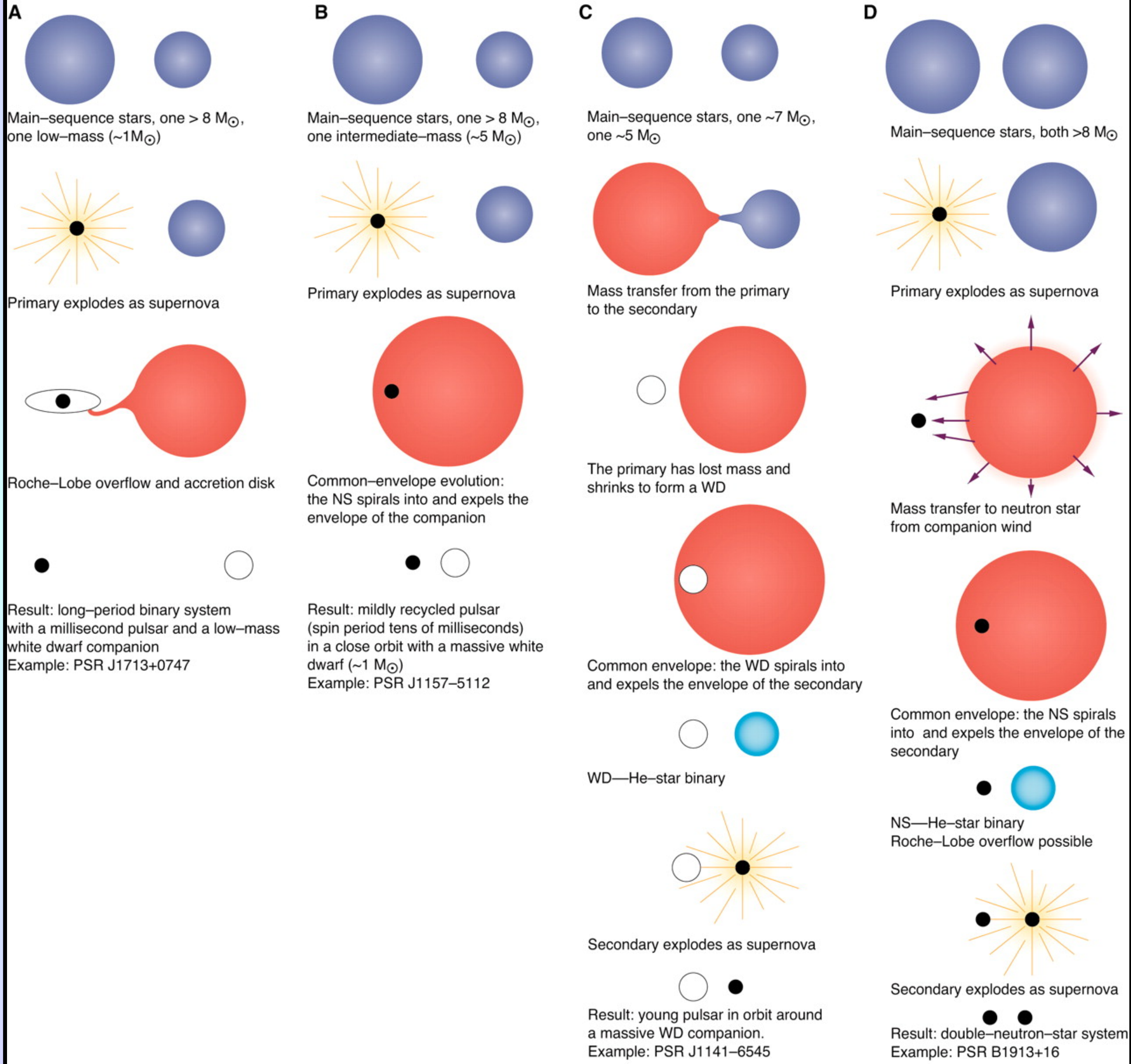
SS 433


Blueshifted radiation
164 days
Jet
78,000 km/sec
To Earth
Jet
Redshifted radiation

SS 433



Hβ
Hδ⁺
Hγ⁺
Hβ⁻
Hβ⁺
HeII
CIII/NIII
HeI
relative flux
3
2
1
4400
4600
4800
5000
5200
5400
wavelength, Å


A
Main–sequence stars, one > 8 M⊙, one low–mass (~1M⊙)
Primary explodes as supernova
Roche–Lobe overflow and accretion disk
Result: long–period binary system with a millisecond pulsar and a low–mass white dwarf companion
Example: PSR J1713+0747
B
Main–sequence stars, one > 8 M⊙, one intermediate–mass (~5 M⊙)
Primary explodes as supernova
Common–envelope evolution: the NS spirals into and expels the envelope of the companion
Result: mildly recycled pulsar (spin period tens of milliseconds) in a close orbit with a massive white dwarf (~1 M⊙)
Example: PSR J1157–5112
C
Main–sequence stars, one ~7 M⊙, one ~5 M⊙
Mass transfer from the primary to the secondary
The primary has lost mass and shrinks to form a WD
Common envelope: the WD spirals into and expels the envelope of the secondary
WD—He–star binary
Secondary explodes as supernova
Result: young pulsar in orbit around a massive WD companion.
Example: PSR J1141–6545
D
Main–sequence stars, both >8 M⊙
Primary explodes as supernova
Mass transfer to neutron star from companion wind
Common envelope: the NS spirals into and expels the envelope of the secondary
NS—He–star binary
Roche–Lobe overflow possible
Secondary explodes as supernova
Result: double–neutron–star system
Example: PSR B1913+16